

UHF Class E/F₂ Outphasing Transmitter for 12 dB PAPR Signals

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Abstract— This paper exploits the degree of freedom provided by the continuous class-E modes in order to reduce the impact of a FET on-state resistance when approximating the zero voltage switching (ZVS) operation along a wide range of resistive loads. A UHF class-E/F₂ power amplifier (PA), which includes a lumped element drain terminating network to synthesize the optimal load modulation (LM) trajectory, has been designed to maintain an efficiency as high as possible along an output power control range above 10 dB. Based on this PA, an outphasing scheme in the 700 MHz frequency band has been implemented. It is shown to provide an efficiency higher than 60% up to an output power below 5% (-13 dB) of its peak value (47 W). Under mixed-mode operation and applying digital predistortion (DPD), a 10 MHz LTE signal with a peak-to-average power ratio (PAPR) as high as 12.2 dB has been linearly reproduced with average efficiency and PAE values of 46.6% and 42.9%, respectively.

Keywords— Chireix, class-E, efficiency, harmonic tuning, LTE, outphasing, power amplifier, UHF, zero voltage switching.

I. INTRODUCTION

Wireless communication systems advance non-stop to the fifth generation (5G) employing spectrum-efficient modulations which result in transmitted signals with unprecedented large PAPR values. Thus, the design of transmitter architectures for 5G and beyond is more challenging than ever to provide high efficient operation whilst satisfying strict linearity requirements.

Traditional efficiency improvement techniques are based on dynamic load modulation or dynamic biasing concepts [1]. Individually, they achieve limited efficiency enhancement at deep power back-off (PBO). Nonetheless, it is possible to increase the power control range where the PA operates efficiently by means of multiway or combined solutions [2], [3]. As a drawback, both circuit complexity and cost increase significantly, demanding more than two active devices. In addition, complex linearization procedures are required.

In the particular case of the outphasing technique, the attention has significantly increased since the integration of load insensitive class-E PAs with non-isolating power combiners [4]. Although theoretically amenable for providing a high efficiency along a wide output power control range, the coverage obtained from real implementations at RF/microwaves is usually limited to values below 10 dB [5]. Among other mechanisms, the on-state resistance (saturation resistance in bipolar devices) stands as the most significant contributor to the remaining losses.

This paper analyzes and exploits the potential of the continuous class-E modes at UHF band to extend the power range to be covered with high efficiency beyond those limits, providing a candidate topology to minimize power consumption when handling signals with extremely high PAPR values. A mixed-mode outphasing operation, combined with DPD, may help satisfying the linearity requirements.

II. VARIABLE LOAD CONTINUOUS-MODE CLASS-E OPERATION

In order to find the appropriate class-E mode to obtain the best possible efficiency versus output power profile from a real device at this frequency band, a packaged GaN HEMT transistor from Cree (CGH35030F) was selected. A switch-type model, including the on-state and off-state resistances, together with the device saturation current [6], was extracted for a biasing point with $V_{GS} = -3.5$ V and $V_{DS} = 28$ V.

In the literature, two different approaches for the definition of the continuum of the class-E operation (assuring ZVS and ZVDS conditions) can be found. On one hand, Acar [7] provided the design parameters for class-E topologies with finite dc-feed inductance for an arbitrary selection of the q parameter, $q = 1/(\omega\sqrt{L_b \cdot C_{out}})$, where L_b and C_{out} are the dc-feed inductance and the output capacitance of the selected device, respectively. On the other hand, Özen [8] defined a continuum of modes for class-E PAs as a function of the reactive termination provided by the output network at the 2nd harmonic while considering an ideal RF-choke biasing coil.

Fig. 1 shows the schematics employed to complete load-pull simulations at f_0 according to both approaches. A 50% duty cycle and negligible transition times were assumed.

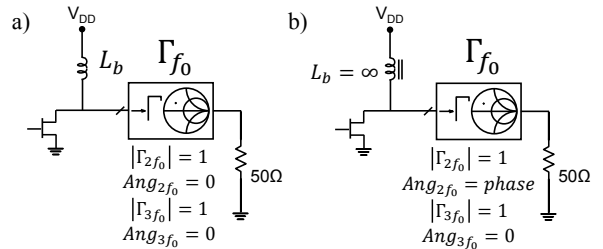


Fig. 1. Schematics to complete load-pull simulations at f_0 for arbitrarily (a) finite dc-feed inductance and (b) reactive 2nd harmonic impedance.

A. Arbitrarily finite dc-feed inductance

According to [7], load-pull simulations were completed as a function of q (see Fig. 2), forcing open circuit terminations at the 2nd and higher order harmonics. Unlike [9], an ideal lossless lumped element network was synthesized for each case, aimed to transform a variable resistance into the optimal LM trajectory.

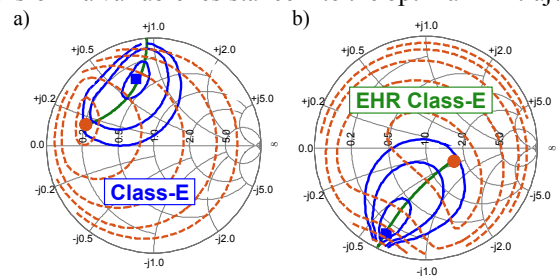


Fig. 2. Output power contours from 33 to 45 dBm with 3 dB step (---) and efficiency contours from 70% to 90% with a 10% step (—) for a) $q = 0$ and b) $q = 2$. The optimal LM trajectory appears in green.

For an ideal switching device, such trajectory would be associated to a ZVS operation. A theoretical 100% efficiency could be consequently expected along it for any value of q . However, the efficiency versus output power profiles are certainly dependent on q for a real transistor, here represented by a switch including conduction losses, as it may be appreciated from Fig. 3. The best performance was achieved for $q=2$, which corresponds to a coil in the biasing path resonating C_{out} at the 2nd harmonic. Compared to the traditional class-E, but also to the $q=1.3$ case, a remarkable efficiency improvement can be observed at power levels well below its maximum. It is interesting to note that this solution was already addressed in the past in the so called even harmonic resonant (EHR) class-E tuned PA without RF choke [10], but operating over a fixed, nominal, load.

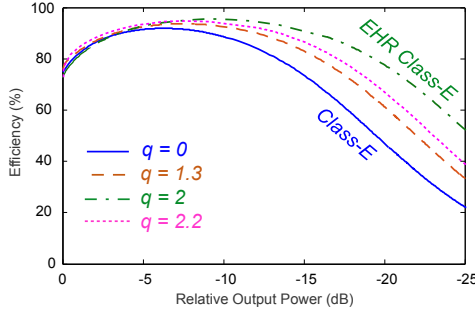


Fig. 3. Efficiency vs. relative or normalized output power as a function of q .

B. Arbitrarily reactive 2nd harmonic termination

The effect of the reactive 2nd harmonic termination was also addressed, as defined in [8]. For different values of the susceptance offered by the output network to the drain terminal, B_{2f_0} , load-pull simulations were completed forcing open circuit terminations at the higher order harmonics (Fig. 4). Synthesizing ideal lossless lumped element networks to follow the optimal LM trajectories, different profiles were obtained (Fig. 5). As in the above case, those trajectories would be associated to a ZVS operation if an ideal switch were employed, leading to a theoretical 100% efficiency profile. However, for a real device, the best performance under varying load resistance was obtained for the susceptance value resonating C_{out} at the 2nd harmonic. The virtual drain plane of the device would be then terminated by an open circuit at $2f_0$, whilst by C_{out} at the higher order harmonics, which would correspond to a class-E/ F_2 operation [11].

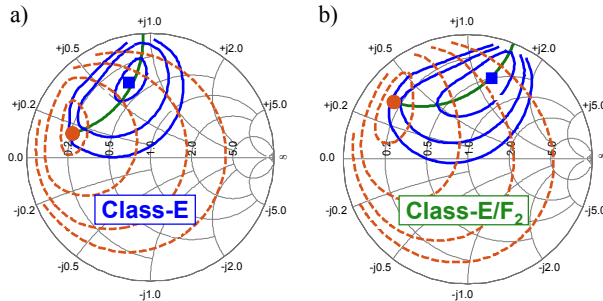


Fig. 4. Output power contours from 36 to 45 dBm with 3 dB step (---) and efficiency contours from 70% to 90% with a 10% step (—) for a) $B_{2f_0} = 0$ and b) $B_{2f_0} = -B_{Cout@2f_0}$. The optimal LM trajectory appears in green.

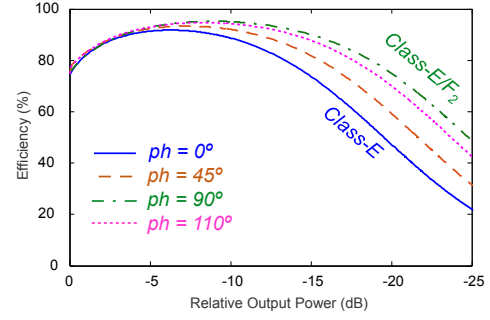


Fig. 5. Efficiency vs. relative output power as a function of the phase in the 2nd harmonic reflection coefficient (a $-B_{Cout@2f_0}$ termination approximately corresponds to $ph=90^\circ$ for the selected device and operating conditions).

Similar simulations, but using the model provided by the supplier, led to the same conclusions regarding the advantages offered by load insensitive EHR and class-E/ F_2 PAs. In both approaches, the efficiency improvement is due to the fact that the *rms* value of the current waveform through the switch is significantly reduced when excluding its 2nd harmonic component [10], [11], leading to minimized losses due to R_{on} . As described in [6], the extracted switch model allowed verifying R_{on} is the main loss contributor for this type of devices when switching at UHF frequencies.

III. LOAD INDEPENDENT CLASS-E/ F_2 PA

Taking into account the previous analysis, a PA capable of efficiently operating along a very wide power control range may be designed either considering the ' $q=2$ ' solution or approaching a class E/ F_2 operation. However, when selecting a real high-Q dc-feed coil for resonating the selected GaN HEMT output capacitance at the 2nd harmonic, the reactance it offers at the fundamental may be so low that the resultant efficiency and output power load-pull contours are very close to each other, far from the expected performance. This is the reason why a class-E/ F_2 topology was preferred for what follows. As explained in [11], it should be taken into account that tuning the $2f_0$ termination may slightly increase the peak value of the drain voltage waveform.

A. Class E/ F_2 PA design

The selected class-E/ F_2 topology, requiring a more complex drain terminating network, is shown in Fig. 6. With the $L_s C_s$ circuit tuned at $2f_0$, L_{b1} is responsible for resonating C_{out} at the 2nd harmonic. L_{b2} was adjusted in order to force the drain biasing network to act as a RF choke at the fundamental.

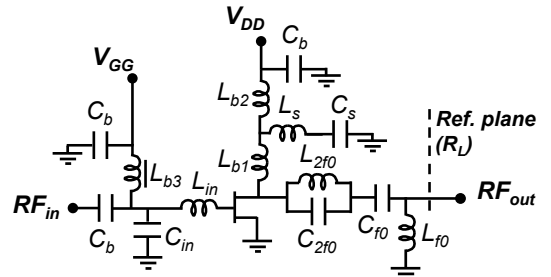


Fig. 6. Schematic of the designed load insensitive class-E/ F_2 PA.

In the RF path, the $L_{2f0}C_{2f0}$ tank resonates at the 2nd harmonic, with C_{f0} and L_{f0} synthesizing the optimal LM trajectory at the fundamental. High Q lumped elements (ATC 100B multilayer capacitors and Coilcraft Air Core coils) have been employed in the implementation.

B. Characterization under variable load resistance

The implemented PA was characterized under variable resistive loading conditions at 700 MHz using the set-up shown in Fig. 7. Each desired load resistance at the reference plane (as can be shown in Fig. 6), was set using a MST981EN Manual Impedance Tuner from Maury Microwave.

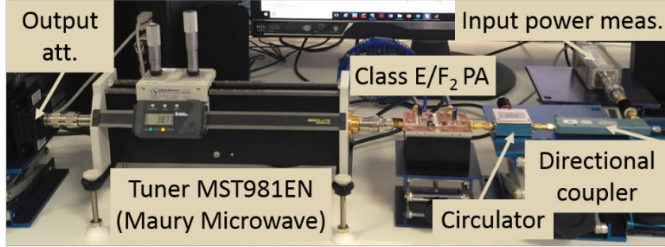


Fig. 7. Test set-up for PA characterization under variable resistive load.

Fig. 8 shows the evolution of the measured parameters with R_L . The drain efficiency remains high for a significant power control range, as expected from simulations. Values of 80% and 70% were measured at power levels 9 dB and 12.7 dB below the peak, respectively. Compared to the results obtained in [6] for a load insensitive PA, but following a class-E topology, the implemented class-E/F₂ PA enhances in 2.7 dB the output power control range for which the drain efficiency stays above 70%.

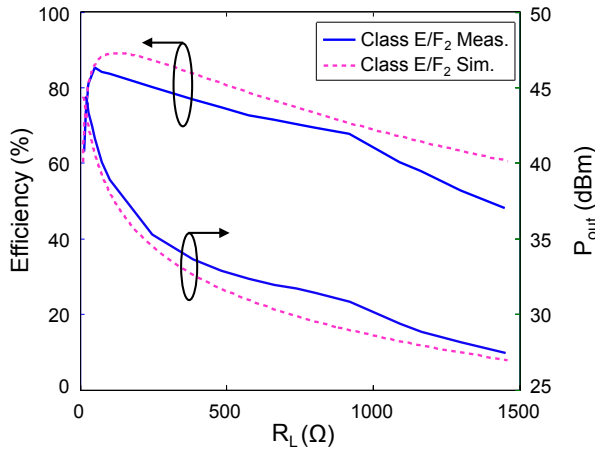


Fig. 8. Simulated (---) and measured (—) efficiency and output power versus load resistance for the Class-E/F₂ PA.

IV. CLASS-E/F₂ OUTPHASING AMPLIFIER

Based on these results, the class-E/F₂ topology could be attractive to efficiently reproduce a signal with a very high PAPR through an outphasing scheme. In Fig. 9a the output power contours from 29 to 44 dBm with 3 dB step and the efficiency contours from 10% to 90% with a 20% step are plotted, once the impact of the real elements in the drain biasing network has been taken into account.

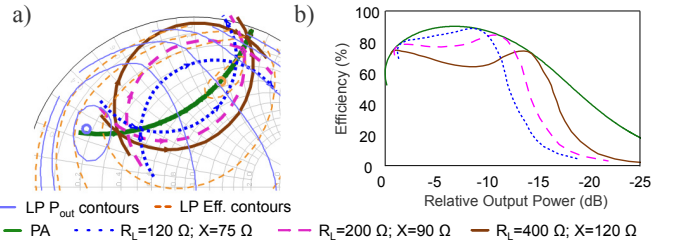


Fig. 9. Simulated a) LM trajectories over the load-pull contours and b) efficiency vs. relative output power profiles.

As it may be observed, the mutual load modulation trajectories should not only cover a wide power range but need also to be shifted towards the edge of the Smith chart. If choosing a series Chireix combiner, this would imply the use of a high compensating reactance, X , and of an impedance transformer with a high transformation ratio, R_L/R_0 with R_0 equal to 50 Ω. In Fig. 9b, a comparison is presented between the simulated profile obtained from the class-E/F₂ PA under variable resistance operation and the ones to be expected from an outphasing scheme with different (ideal) X and R_L values. As it can be observed, the characteristics of the outphasing solutions are bounded by the PA one.

A. Design and implementation

A simple combiner, including an L-type $L_t C_t$ transformer, was used (see Fig. 10a). L_{chx} , C_{chx} , L_t and C_t were selected to synthesize X and R_L values around 90 Ω and 200 Ω, respectively. Fig. 10b shows a photograph of the implementation.

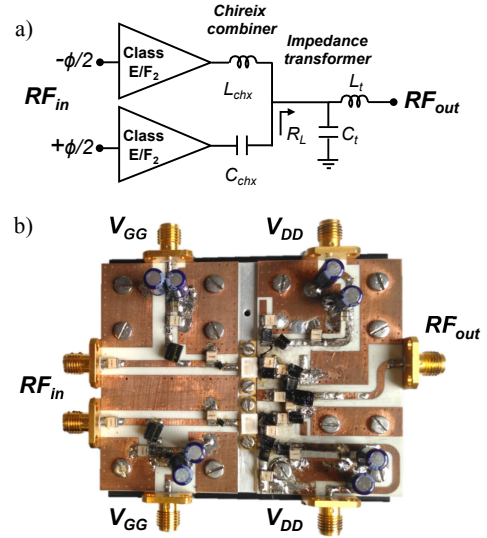


Fig. 10. Implemented outphasing topology: (a) Schematic and (b) photograph.

B. Static characterization

The class-E/F₂ Chireix amplifier was characterized in pure outphasing mode (Fig. 11). The bandwidth, where the efficiency remains higher than 50% at 13 dB of output PBO, was estimated to be around 17 MHz. The operation at very light loading condition is highly selective in frequency. At 700 MHz, an efficiency peak of 70% was measured for 11.9 dB of output PBO, remaining above 60% up to a power level as low as 4.5% (-13.45 dB) of the peak or nominal output power (47 W).

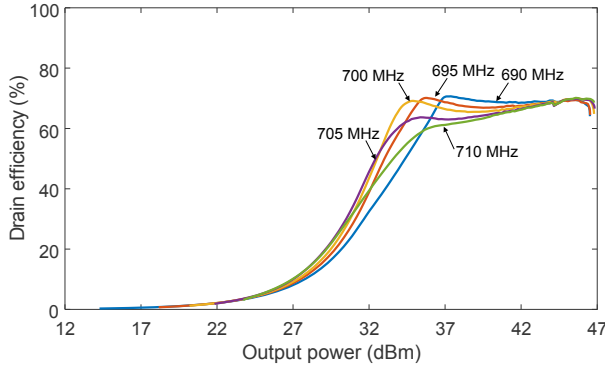


Fig. 11. Measured drain efficiency versus output power profiles at different frequencies in pure outphasing operating mode.

C. Dynamic characterization

The hardware was finally tested using LTE signals with highly demanding PAPR values. A mixed-mode operation [12] was selected, due to the need for accurately reproducing the lowest part of the envelope besides its advantages in terms of average PAE. The gate biasing voltage was slightly increased above pinch-off to operate the PAs in a sort of class-J mode when allowing envelope variations in the input signals (reproduction of envelope values up to 12 dB below the peak). Average efficiency/PAE figures of 57.6%/54.9% and 46.6%/42.9% were measured for signals with 1.4 MHz and 10 MHz bandwidth, respectively, once the linearity requirements were satisfied. Fig. 12 shows the output spectra, before and after DPD, for the 10 MHz LTE signal with a 12.2 dB PAPR. Table 1 compares these results with those from representative state-of-the-art GaN HEMT outphasing PAs. The employed DPD, based on [13], combines lookup tables with a generalized memory polynomial behavioral model (GMP-LUT).

V. CONCLUSION

The degree of freedom provided by the continuum of the class-E mode has been exploited to design a load modulated UHF PA capable of maintaining high efficiency over an output power control range as wide as possible. Integrating load insensitive class-E/F₂ PAs in a 700 MHz outphasing scheme, an efficiency better than 60% up to a power level 13.45 dB below its peak (47 W) was measured, when working in pure outphasing mode. Taking advantage of a mixed-mode operation with the aid of a GMP-LUT DPD, a 10 MHz LTE signal with a very high 12.2 dB PAPR value has been linearly recovered (ACLR < -45 dBc) with average efficiency and PAE values of 46.6% and 42.9%, respectively.

Table 1. Comparison with state-of-the-art outphasing PAs.

Ref.	f_0 (GHz)	η_{DPA} @ 10 dB / 13 dB (%)	P_{out_max} (W)	Signal/PAPR (dB)	Worst ACLR (dBc)	η_{avg} (%)
[6]	0.7	70 / 44	55	1.4 MHz LTE / 9.6	-44.2	52.5
This work	0.7	66.7 / 64	47.75	1.4 MHz LTE / 11.8	-45	57.6
[14]	2.1	≈40* / ≈30*	29.2	10 MHz LTE / 12.2	-45	46.6
[15]**	2.14	50 / ≈40	110	20 MHz LTE / 9	-51	55
[9]	2.3	55 / ≈43	70.6	3.84 MHz WCDMA / 9.15	-33	55.6
[3]***	9.7	≈48 / ≈45	5	3.84 MHz WCDMA / 9.6	-49	53.5
				1.4 MHz LTE / 9.3	-41.6	38
				10 MHz LTE / 11.3	-31.5	25.6

*PAE **Four-way ***Multi-level Supply Modulated

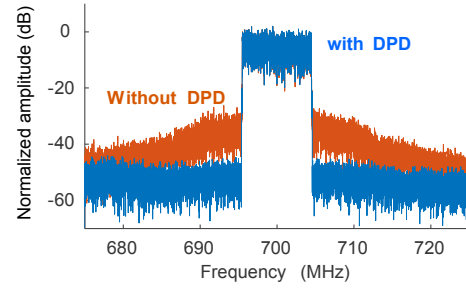


Fig. 12. Normalized output spectra (10 MHz LTE signal), before and after DPD.

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